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Title: Multiparameter full-waveform inversion in complex media applied to walk-away vertical seismic profile data

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Multiparameter full-waveform inversion in complex media applied to walk-away vertical seismic profile data

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CALGARY



CREWES

Outline

- ① Why do we need to do full-waveform inversion (FWI) ?
- ② Challenges of Multiparameter FWI
- ③ Model Parameterization Analysis in Isotropic-elastic FWI
- ④ VTI-elastic FWI
- ⑤ Conclusions

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Why do we need to do FWI ?

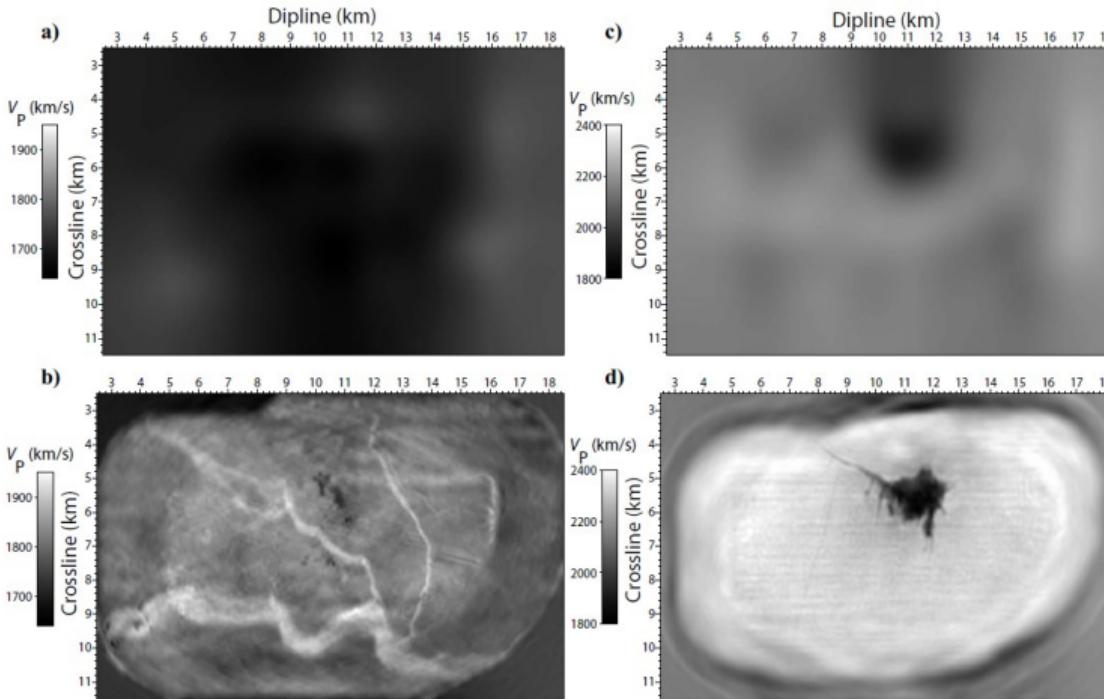
- Most of previous seismic inversion methods approximate wave propagation in subsurface:
 - Ray-tracing traveltime tomography: high-frequency approximation;
 - Seismic AVO inversion: linear approximations of Zoeppritz equation;
 - Deconvolution: convolution model;
 -

Why do we need to do FWI ?

- FWI inverts for subsurface properties by numerically solving the wave equation:

Why do we need to do FWI ?

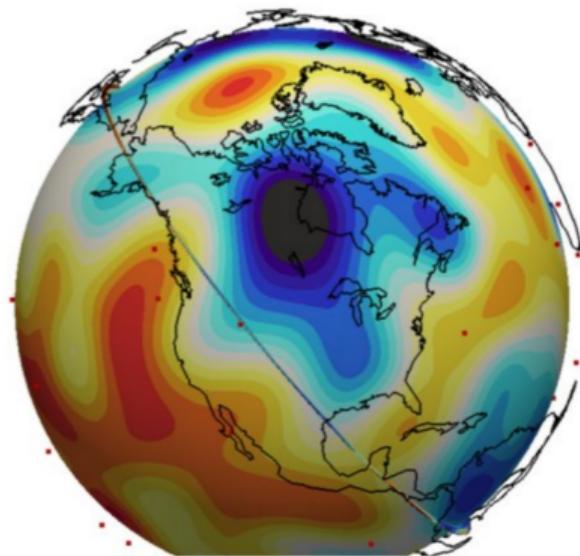
Compared to ray-based methods, FWI can provide high-resolution velocity models.



Adapted from Virieux and Operto, 2009.

Why do we need to do FWI ?

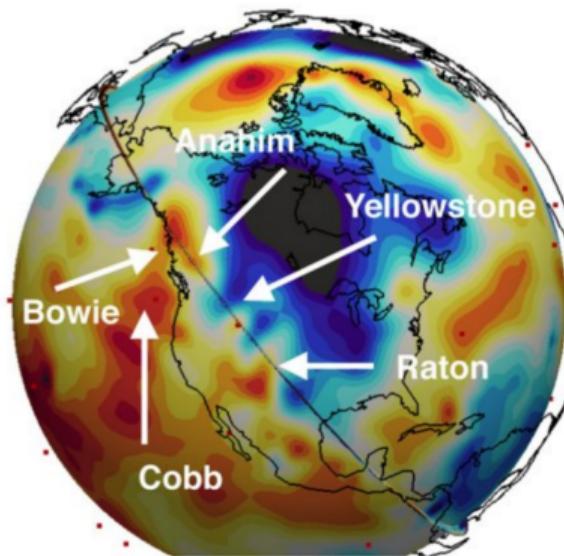
S362ANI



$d\ln V_{sv}$ (2%)

min ————— max

GLAD-M15



$d\ln V_{sv}$ (2%)

min ————— max

Adapted from Bozdag et al. , 2016.

Outline

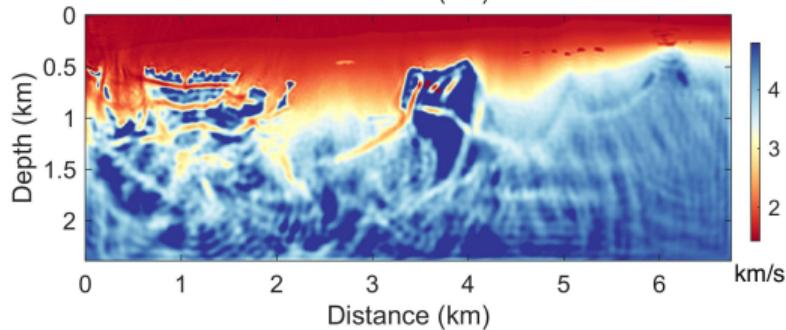
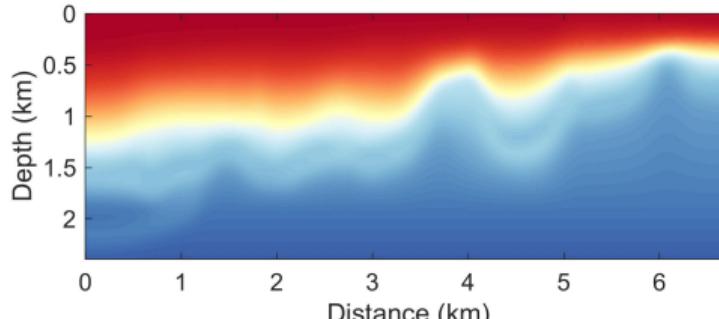
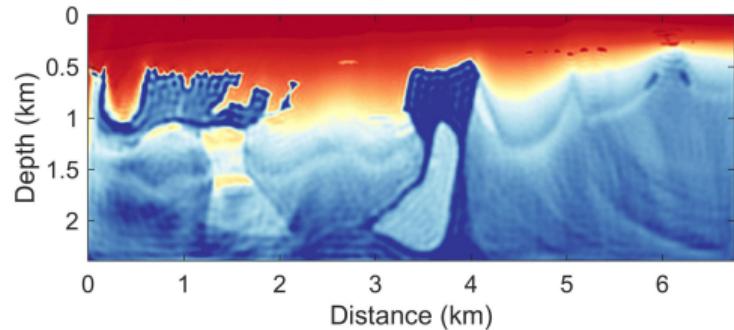
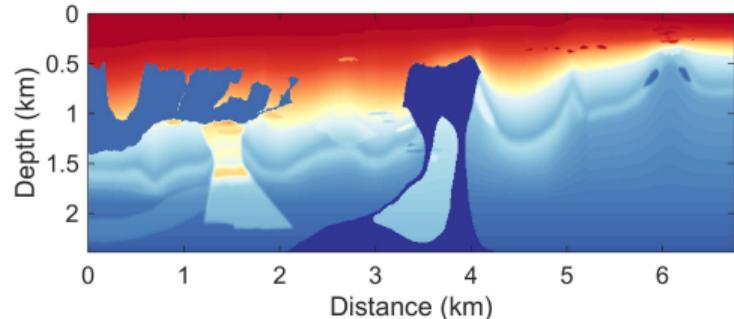
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Challenges of Multiparameter FWI

- High nonlinearity of the inverse problem results in **cycle-skipping** problem.
 - Inaccurate initial model;
 - Lack of low frequencies in the seismic data (exploration scale);
- **Interparameter tradeoffs** increase nonlinearity and uncertainty of multiparameter FWI.
- High computational requirements.
-

Challenges of Multiparameter FWI

- Illustration of the **cycle-skipping** problem:



Challenges of Multiparameter FWI

- When inverting for multiple physical parameters, the errors in one physical parameter are mapped into the estimation of another one, which is known as the [interparameter tradeoff](#) problem in multiparameter FWI.

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Model Parameterization Analysis in Isotropic-elastic FWI

The augmented Lagrangian misfit function in FWI is:

$$\begin{aligned}\chi(\mathbf{m}) = & \frac{1}{2} \sum_{\mathbf{x}_r} \int_0^{t'} [u_i(\mathbf{x}_r, t; \mathbf{m}) - u_i^{\text{obs}}(\mathbf{x}_r, t)]^2 dt \\ & - \int_0^{t'} \int_{\Omega} \lambda_i(\mathbf{x}, t) \{ \rho(\mathbf{x}) \partial_t^2 u_i(\mathbf{x}, t) - \partial_j [c_{ijkl}(\mathbf{x}) \partial_l u_k(\mathbf{x}, t)] - f_i(\mathbf{x}_s) \} d\mathbf{x} dt,\end{aligned}$$

where u_i and u_i^{obs} are the synthetic and observed data, and in isotropic-elastic media, c_{ijkl} is

$$c_{ijkl} = \left(\kappa - \frac{2}{3} \mu \right) \delta_{ij} \delta_{kl} + \mu (\delta_{ik} \delta_{jl} + \delta_{jk} \delta_{il}),$$

where κ and μ are bulk and shear modulus. Variation of the misfit function is given by

$$\Delta \chi = \int_{\Omega} [K_{\kappa}(\mathbf{x}) \Delta \kappa(\mathbf{x}) + K_{\mu}(\mathbf{x}) \Delta \mu(\mathbf{x}) + K_{\rho}(\mathbf{x}) \Delta \rho(\mathbf{x})] d\mathbf{x}.$$

Model Parameterization Analysis in Isotropic-elastic FWI

The sensitivity kernels K_κ , K_μ and K_ρ are:

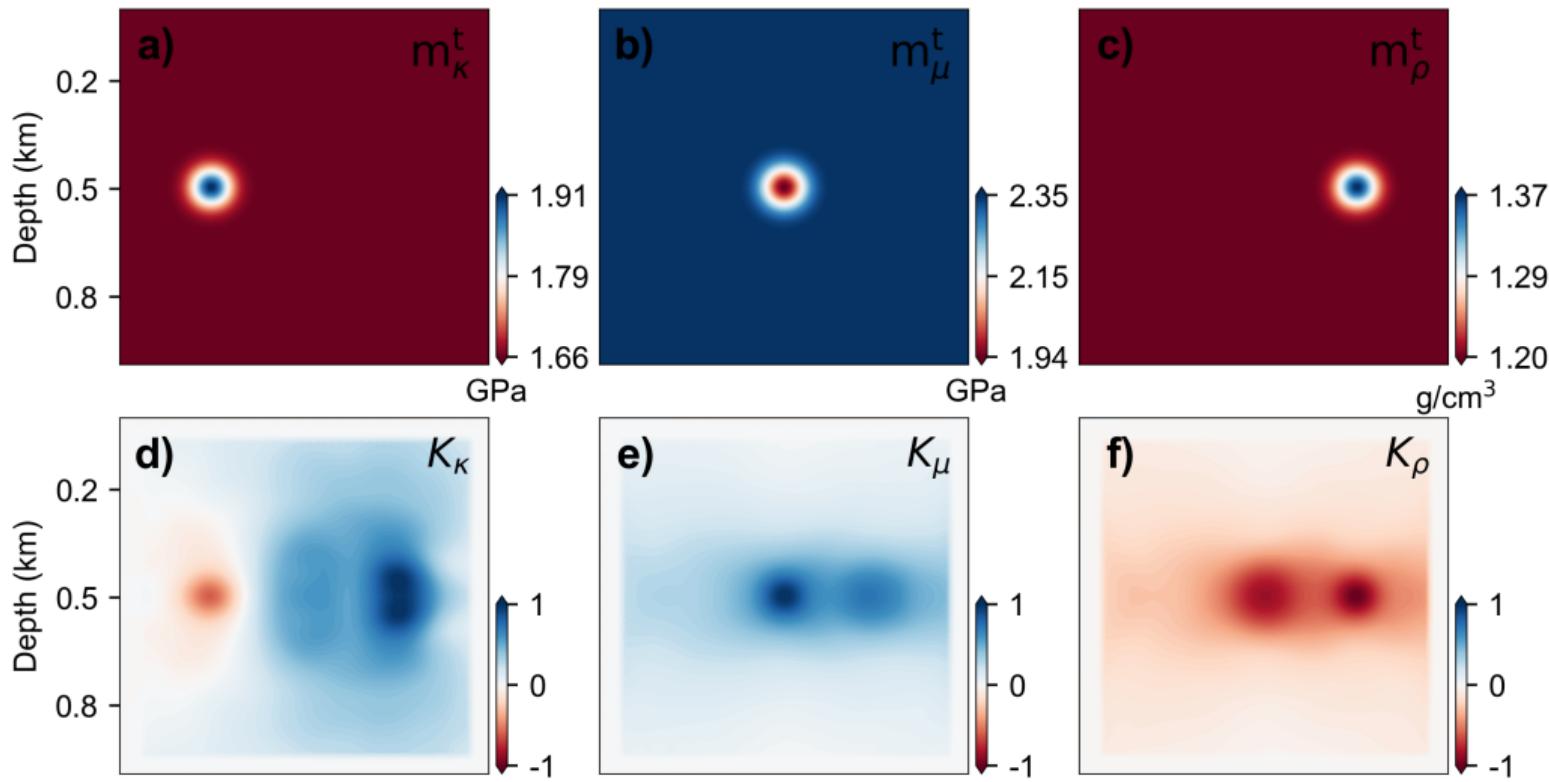
$$K_\kappa = - \ll \partial_i \tilde{u}_i \partial_k u_k \gg,$$

$$K_\mu = - \ll \partial_j \tilde{u}_i (\partial_i u_j + \partial_j u_i) - \frac{2}{3} \partial_i \tilde{u}_i \partial_k u_k \gg,$$

$$K_\rho = - \ll \tilde{u}_i \partial_t^2 u_i \gg.$$

- **Interparameter tradeoffs** appear when determining multiple physical parameters.
- The errors in one parameter (i.e., μ) produce influences to the estimation of another (i.e., ρ).

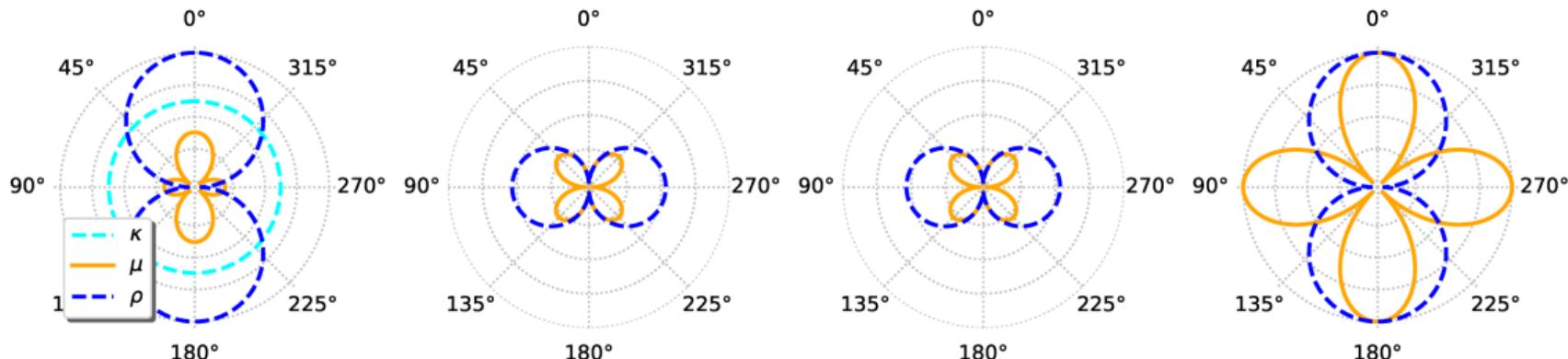
Model Parameterization Analysis in Isotropic-elastic FWI



Model Parameterization Analysis in Isotropic-elastic FWI

Qualitative analysis with scattering radiation patterns

$$d_n(\mathbf{x}_r, \mathbf{x}_s, t) \approx - \sum_p \int_0^t \int_{\mathbf{x} \in \Omega} [\mathbf{\hat{A}}_j^p G_{nj}(\mathbf{x}_r, \mathbf{x}, t)] a_p(\mathbf{x}) f_i(\mathbf{x}_s, t') [\mathbf{\hat{A}}_k^p G_{ki}(\mathbf{x}, \mathbf{x}_s, t - t')] d\mathbf{x} dt'.$$



- Scattering patterns overlap significantly indicating strong tradeoffs.

Model Parameterization Analysis in Isotropic-elastic FWI

Quantifying interparameter tradeoffs with [interparameter contamination kernel \(ICK\)](#).

Newton equation in multiparameter inversion is:

$$\begin{bmatrix} \mathbf{H}_{\kappa\kappa} & \mathbf{H}_{\kappa\mu} & \mathbf{H}_{\kappa\rho} \\ \mathbf{H}_{\mu\kappa} & \mathbf{H}_{\mu\mu} & \mathbf{H}_{\mu\rho} \\ \mathbf{H}_{\rho\kappa} & \mathbf{H}_{\rho\mu} & \mathbf{H}_{\rho\rho} \end{bmatrix} \begin{bmatrix} \Delta\kappa \\ \Delta\mu \\ \Delta\rho \end{bmatrix} = - \begin{bmatrix} K_\kappa \\ K_\mu \\ K_\rho \end{bmatrix},$$

which can be re-written as:

$$\begin{aligned} K_\kappa(\mathbf{x}) &= - \int_{\Omega} [H_{\kappa\kappa}(\mathbf{x}, \mathbf{x}') \Delta\kappa(\mathbf{x}') + H_{\kappa\mu}(\mathbf{x}, \mathbf{x}') \Delta\mu(\mathbf{x}') + H_{\kappa\rho}(\mathbf{x}, \mathbf{x}') \Delta\rho(\mathbf{x}')] d\mathbf{x}' \\ &= K_{\kappa \leftrightarrow \kappa}(\mathbf{x}) + K_{\mu \rightarrow \kappa}(\mathbf{x}) + K_{\rho \rightarrow \kappa}(\mathbf{x}). \end{aligned}$$

$$\begin{aligned} K_\mu(\mathbf{x}) &= - \int_{\Omega} [H_{\mu\kappa}(\mathbf{x}, \mathbf{x}') \Delta\kappa(\mathbf{x}') + H_{\mu\mu}(\mathbf{x}, \mathbf{x}') \Delta\mu(\mathbf{x}') + H_{\mu\rho}(\mathbf{x}, \mathbf{x}') \Delta\rho(\mathbf{x}')] d\mathbf{x}' \\ &= K_{\kappa \rightarrow \mu}(\mathbf{x}) + K_{\mu \leftrightarrow \mu}(\mathbf{x}) + K_{\rho \rightarrow \mu}(\mathbf{x}). \end{aligned}$$

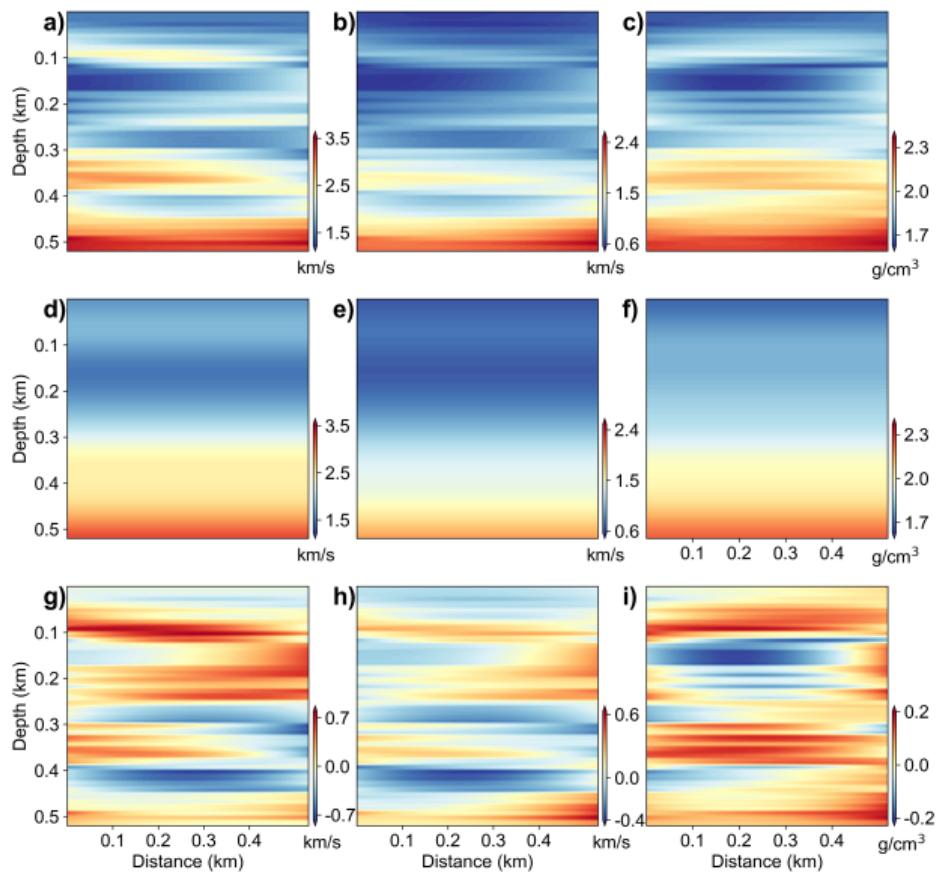
Model Parameterization Analysis in Isotropic-elastic FWI

Isotropic-elastic media can be described using different model parameterizations:

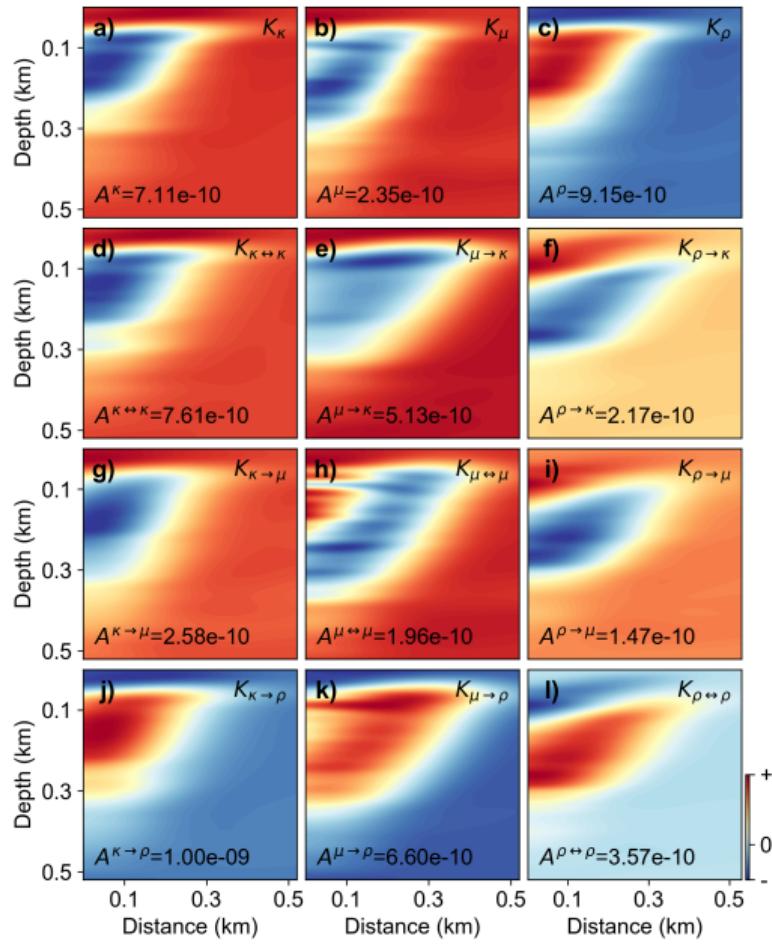
- Modulus-density (κ , μ and ρ)
- Velocity-density (α , β and ρ')
- Impedance-density (I_P , I_S and ρ'')
-

Different model parameterizations have different tradeoffs and inversion performances.

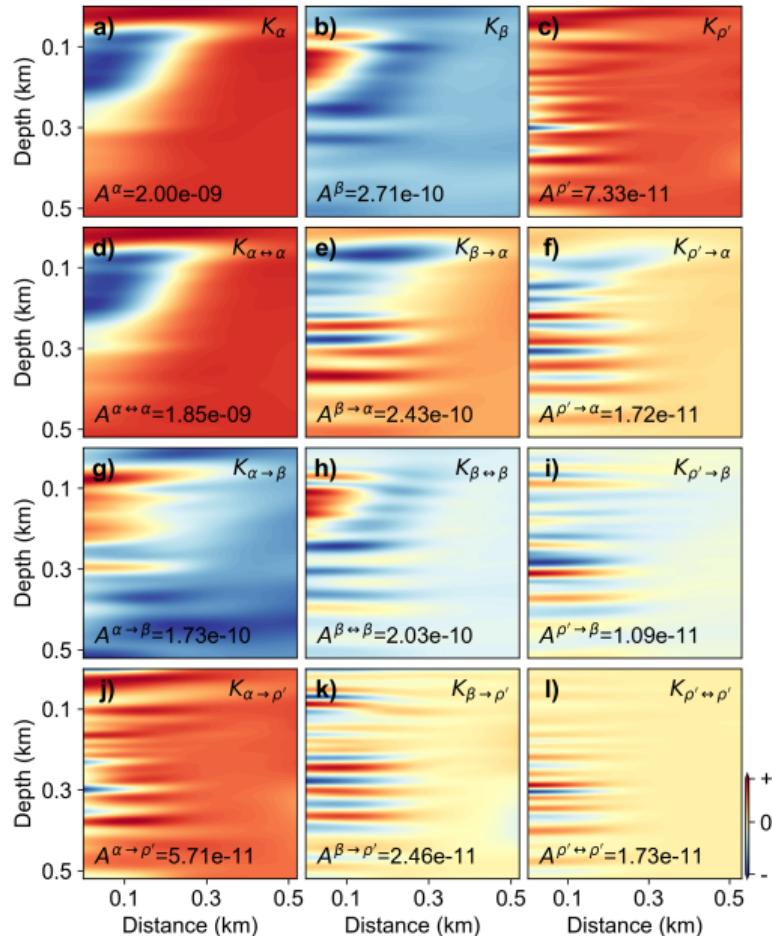
- Synthetic example with walkaway vertical seismic profile (W-VSP) data;
- The first row shows true α , β and ρ' models. The second and third rows are the initial models and true model perturbations;



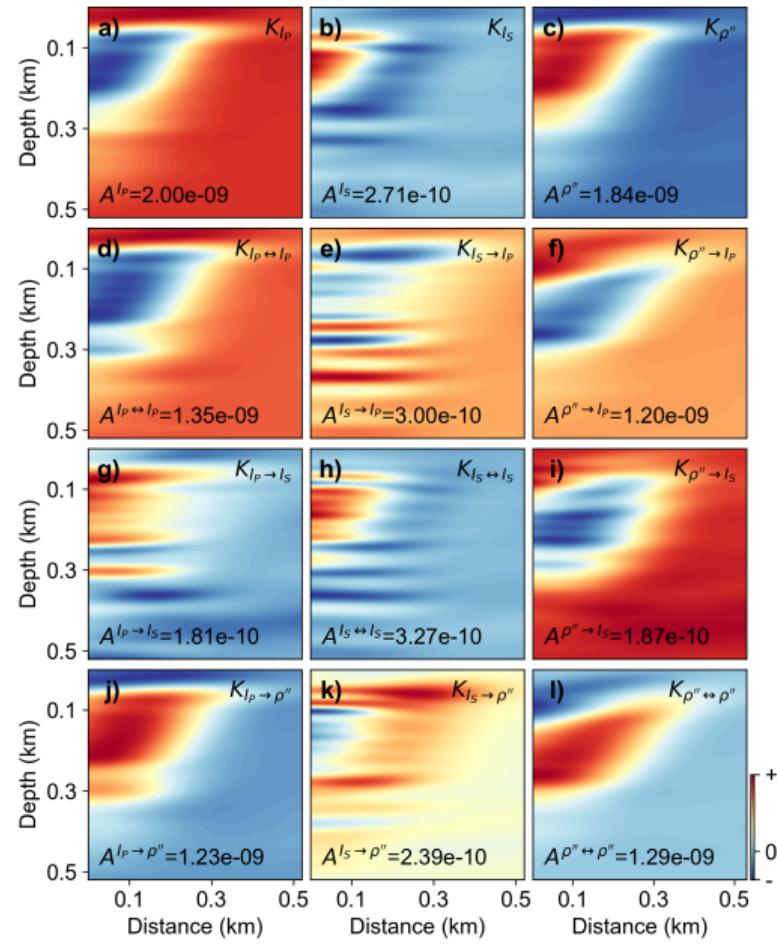
- The κ perturbation produces strong and polarity-reversed artifacts into ρ update at low wavenumber;
- In modulus-density parameterization, the ρ parameter suffers from the strongest interparameter tradeoffs;



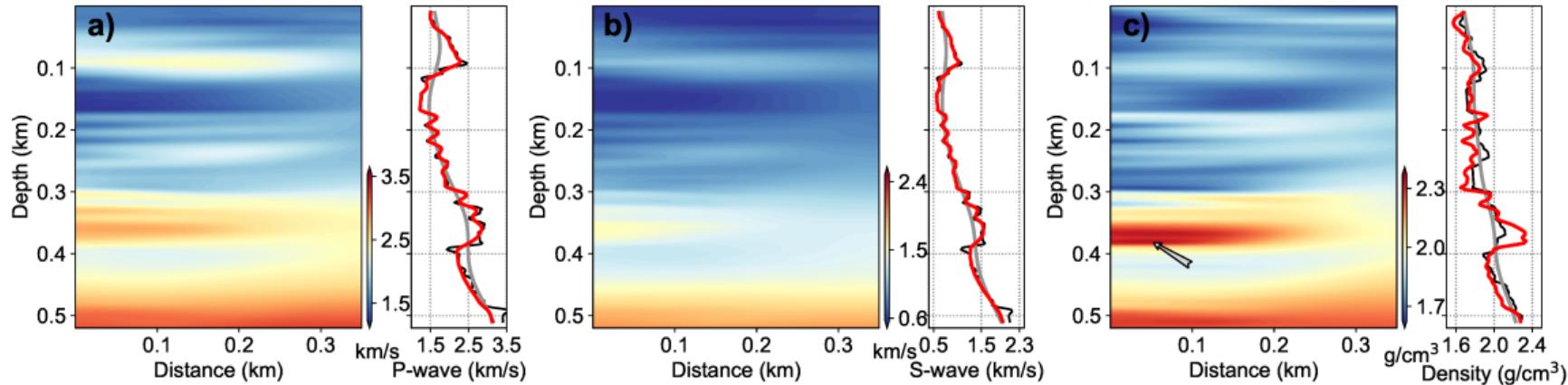
- The α perturbation produces strong artifacts into ρ' update at high wavenumber;
- In velocity-density parameterization, the ρ' parameter suffers from the strongest interparameter tradeoffs;



- The I_P perturbation produces strong and polarity-reversed artifacts into ρ'' update at low wavenumber;
- In impedance-density parameterization, the ρ'' parameter suffers from the strongest interparameter tradeoffs;

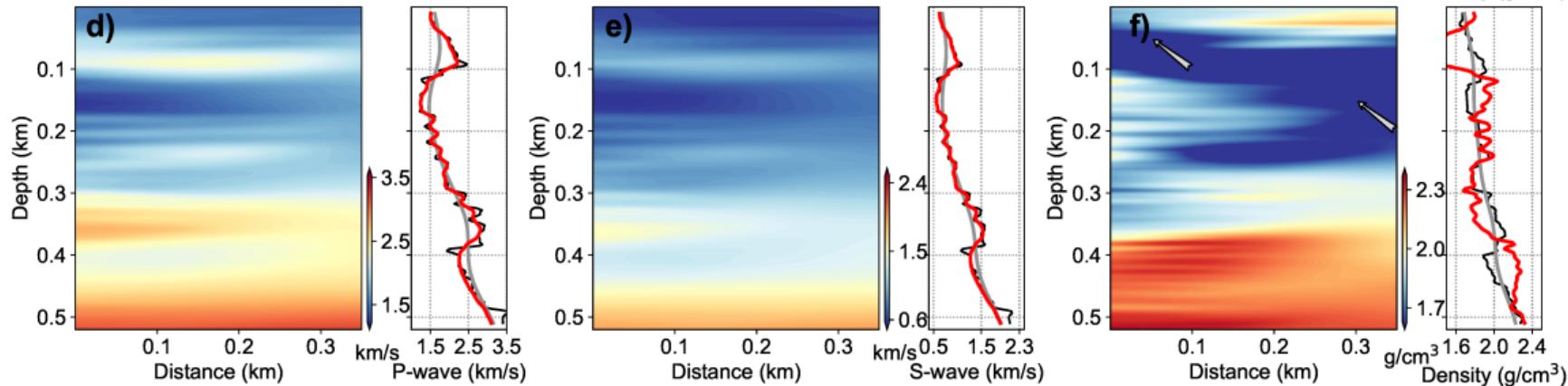


Model Parameterization Analysis in Isotropic-elastic FWI



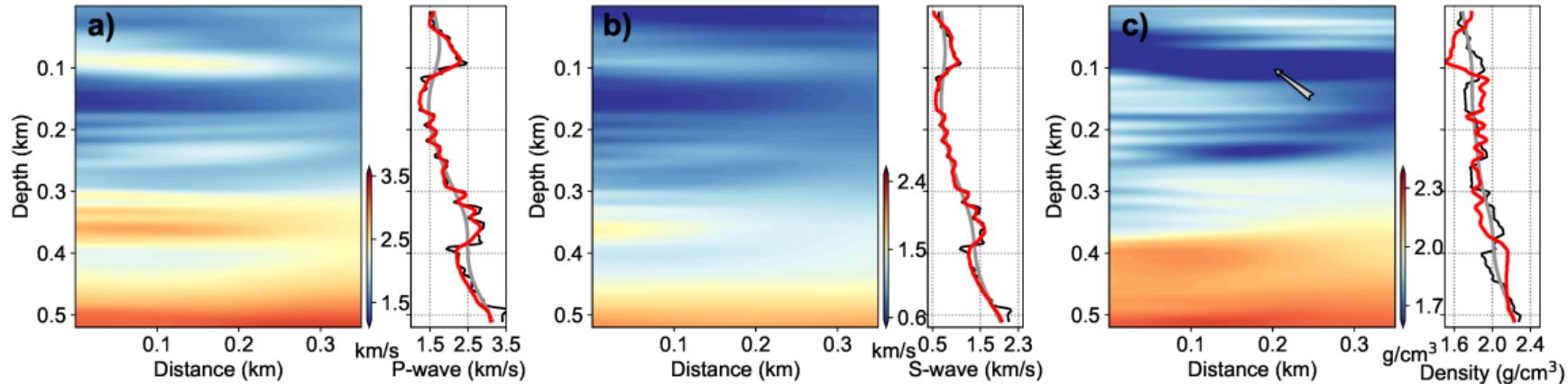
The inverted α , β and ρ' models using velocity-density model parameterization.

Model Parameterization Analysis in Isotropic-elastic FWI



The inverted α , β and ρ' models using modulus-density model parameterization.

Model Parameterization Analysis in Isotropic-elastic FWI

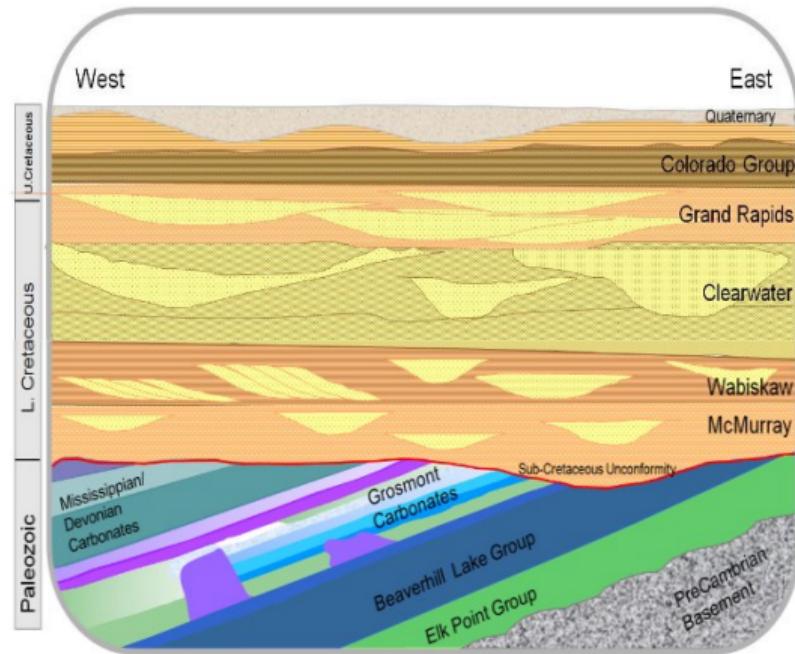


The inverted α , β and ρ' models using impedance-density model parameterization.

Model Parameterization Analysis in Isotropic-elastic FWI



Location of the studied area



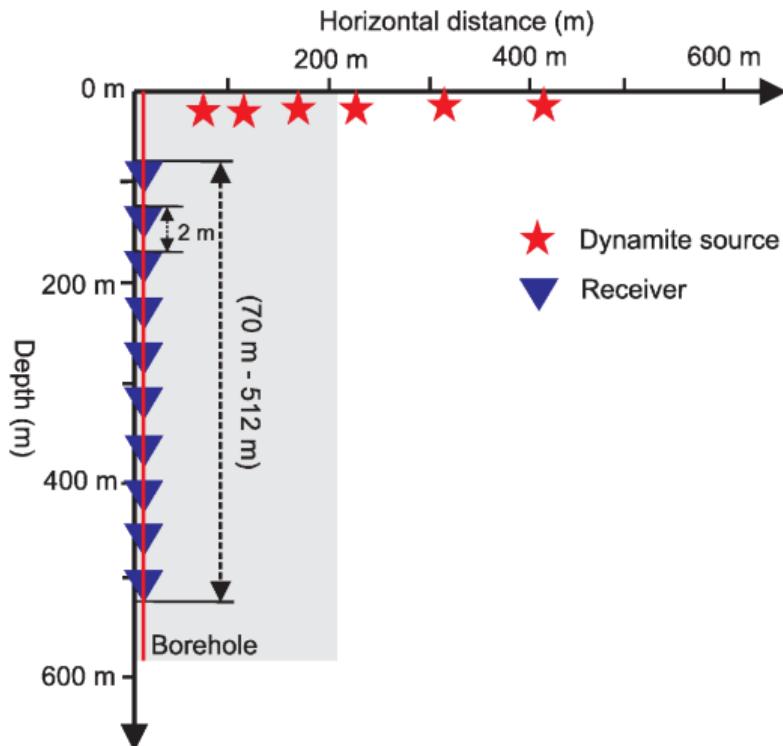
Model Parameterization Analysis in Isotropic-elastic FWI



Location of the studied area

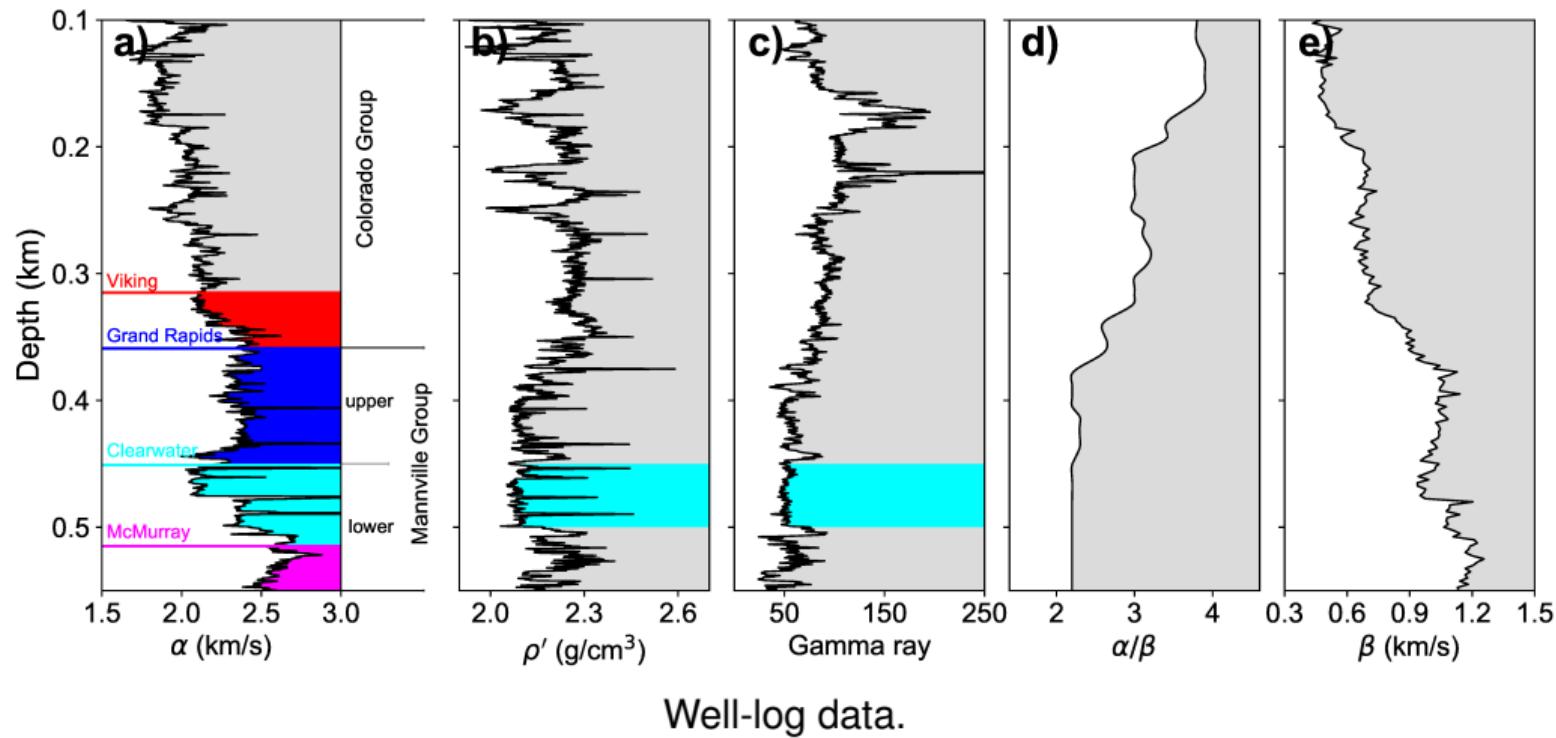


Model Parameterization Analysis in Isotropic-elastic FWI

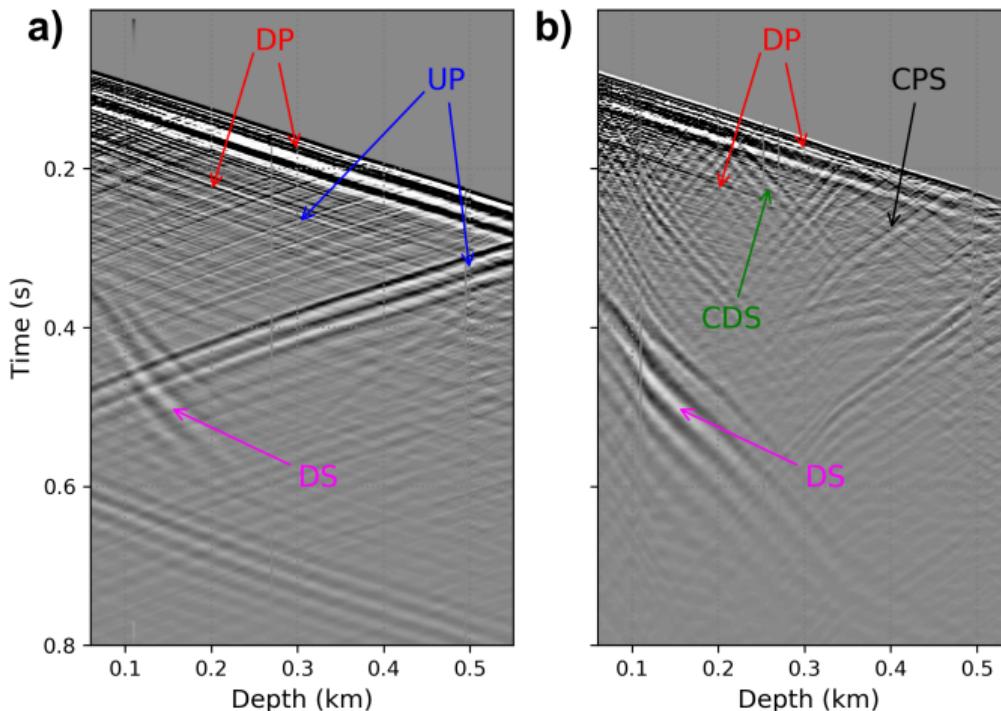


The W-VSP data acquisition geometry.

Model Parameterization Analysis in Isotropic-elastic FWI

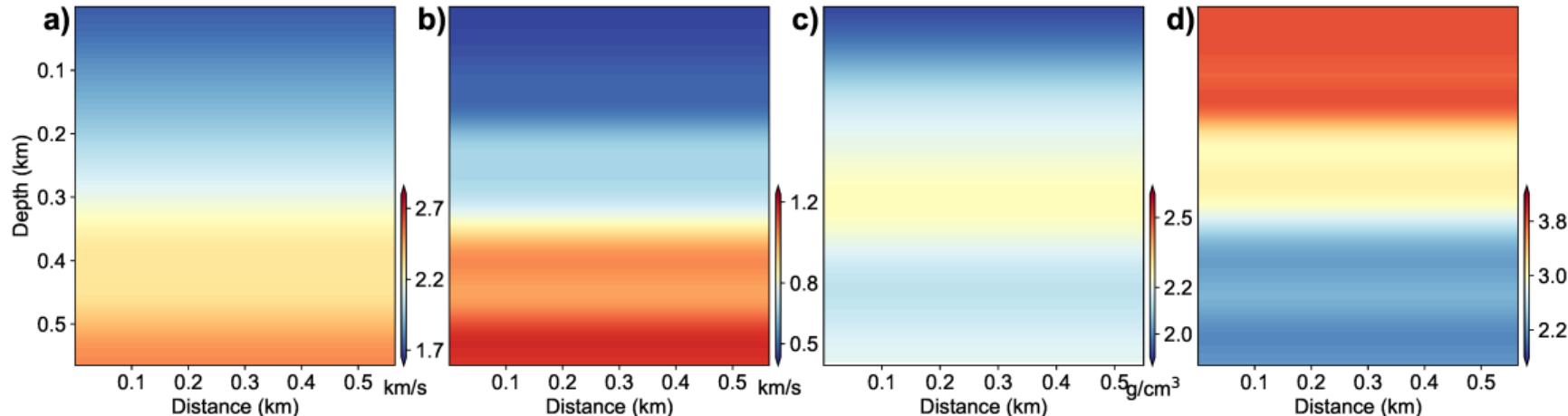


Model Parameterization Analysis in Isotropic-elastic FWI



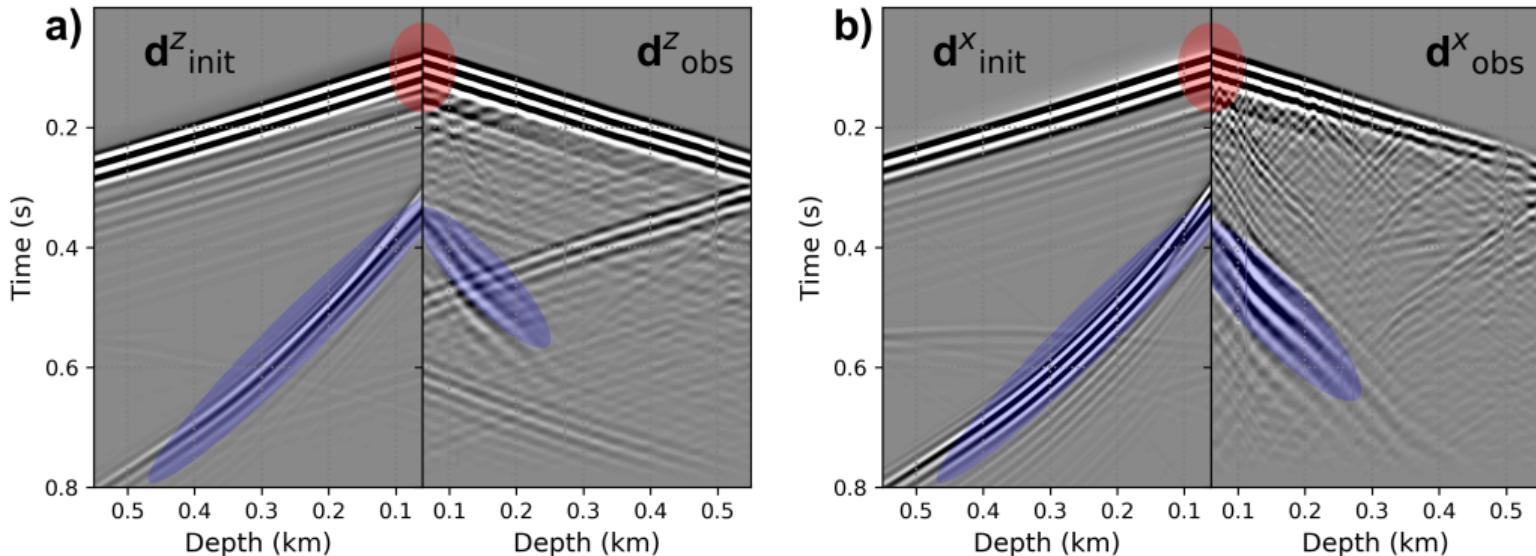
Vertical and radial component of the observed data.

Model Parameterization Analysis in Isotropic-elastic FWI

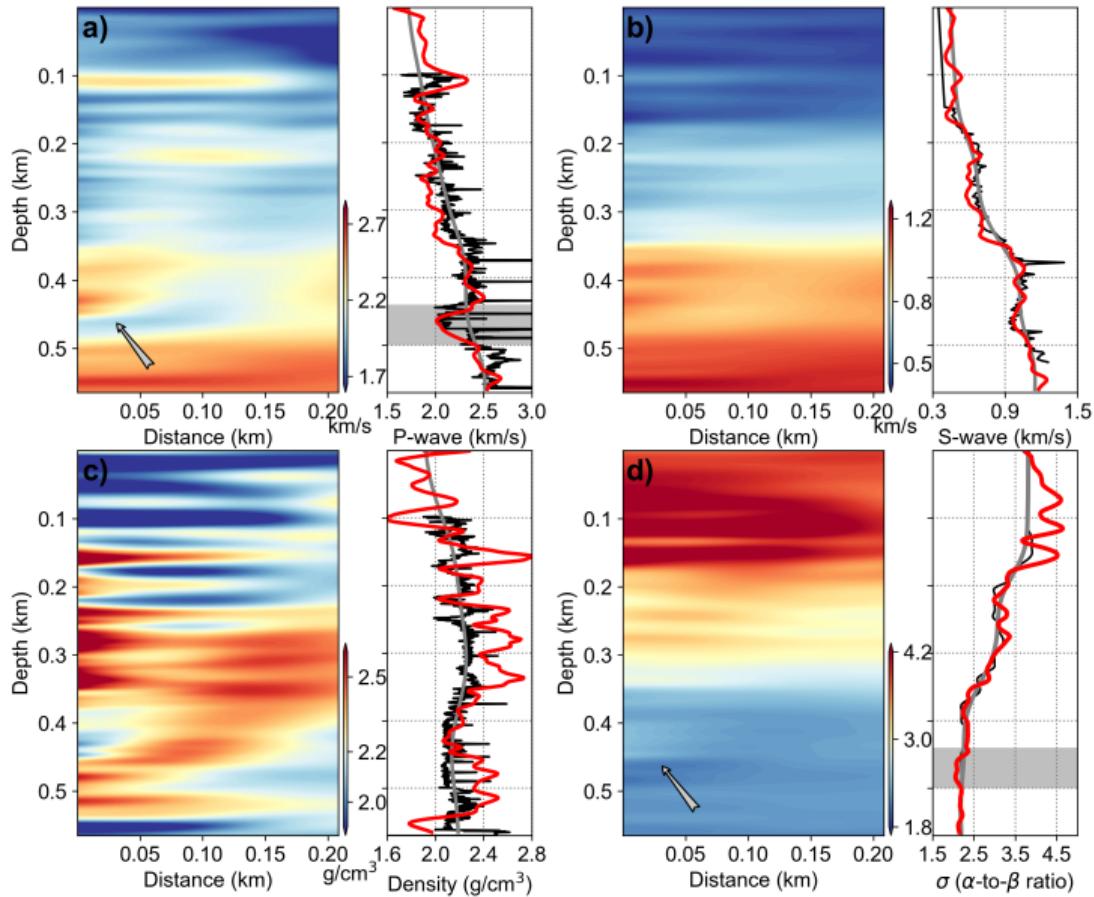


The initial α , β , ρ' and α/β models.

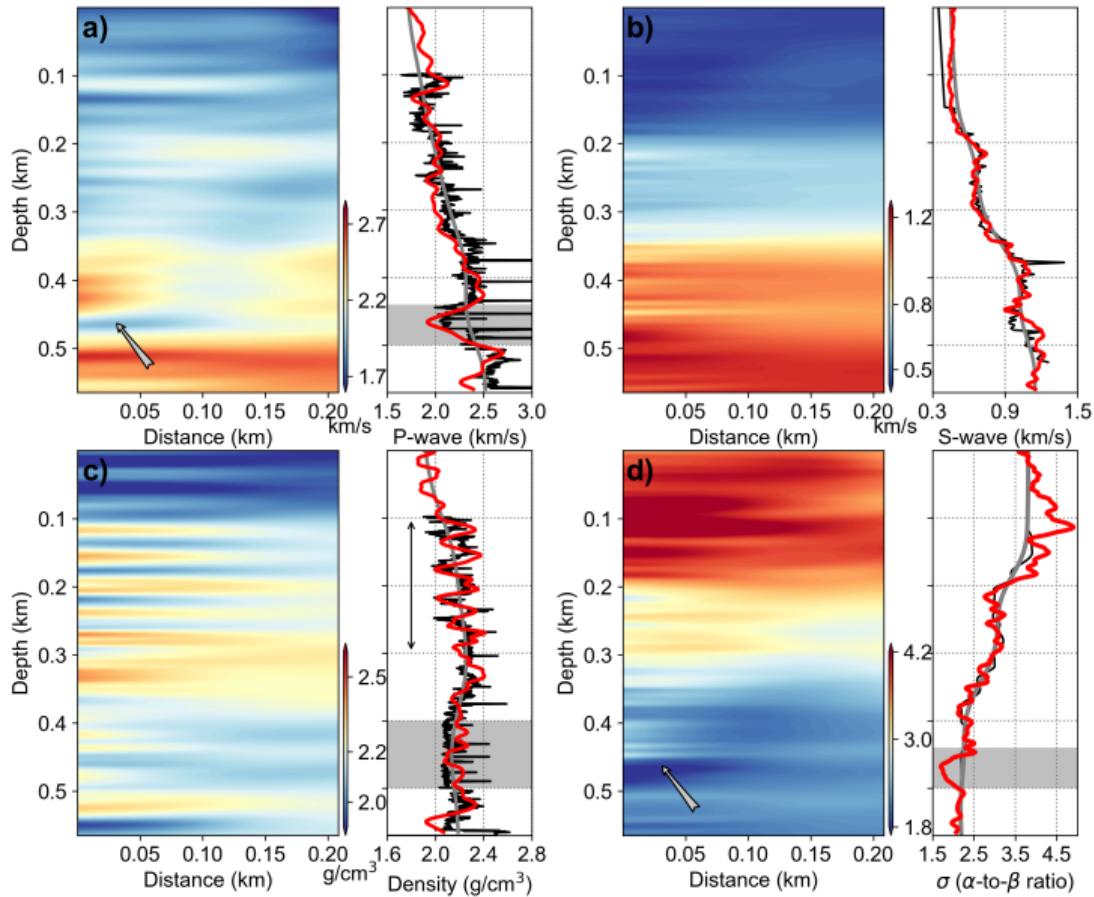
Model Parameterization Analysis in Isotropic-elastic FWI



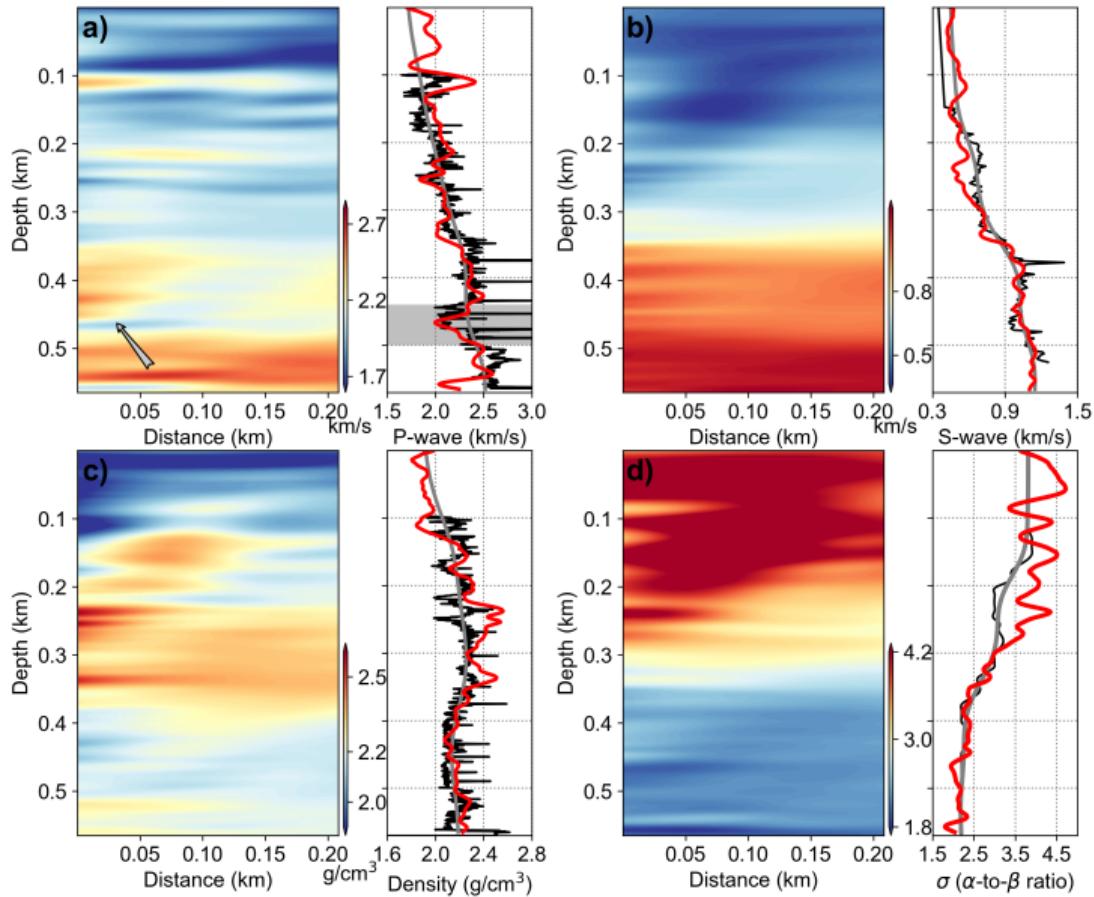
Comparison of the observed data and synthetic data produced from initial models.



The inverted α , β , ρ' and α/β models using modulus-density parameterization.

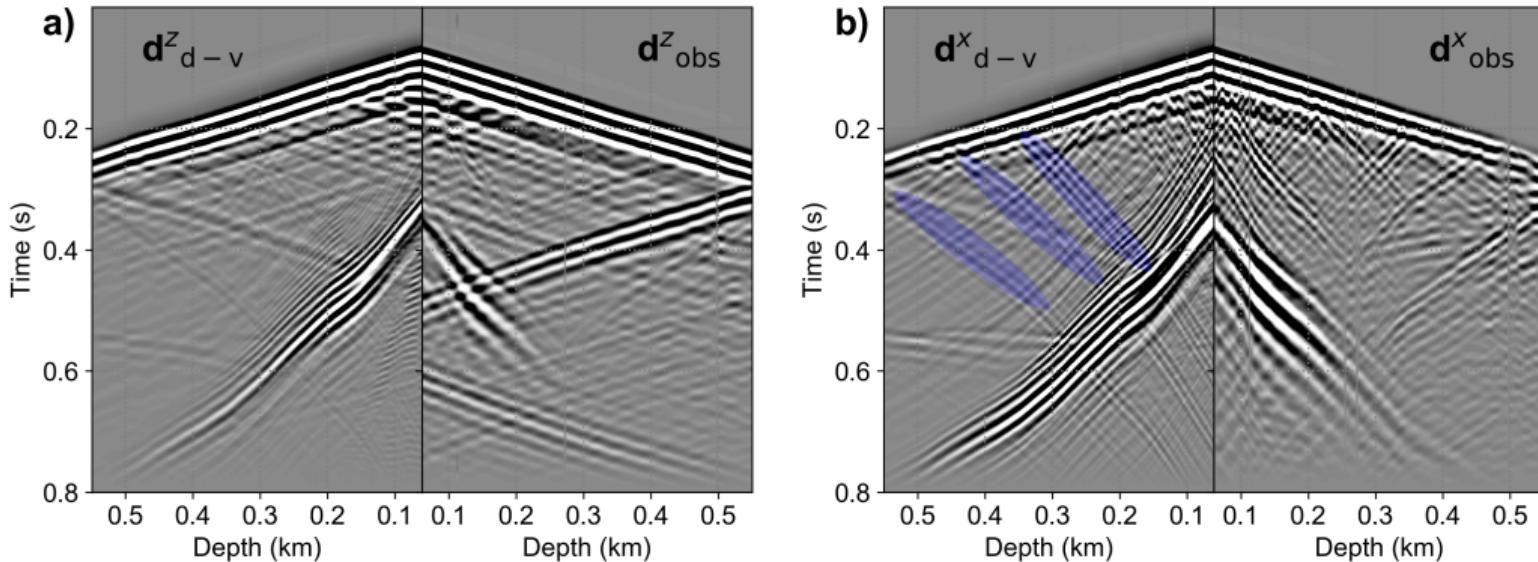


The inverted α , β , ρ' and α/β models using velocity-density parameterization.



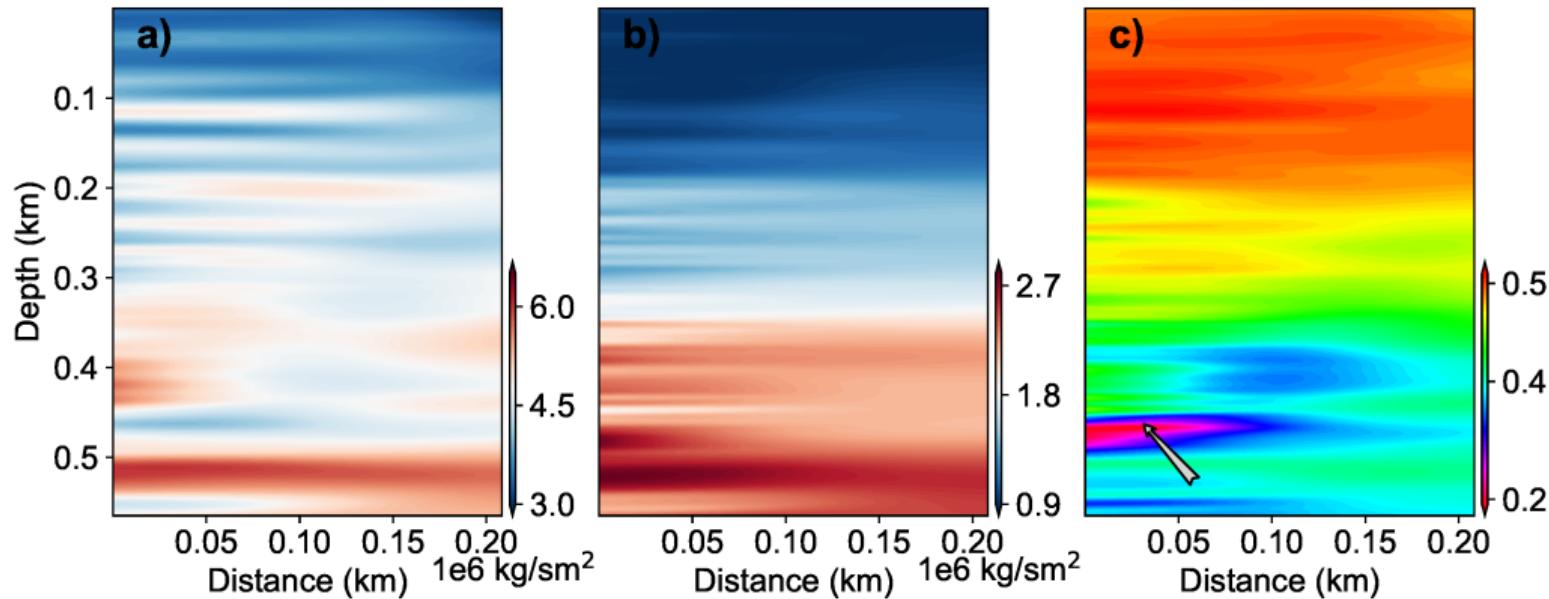
The inverted α , β , ρ' and α/β models using impedance-density parameterization.

Model Parameterization Analysis in Isotropic-elastic FWI



Comparison of the observed data and synthetic data produced from inverted models.

Model Parameterization Analysis in Isotropic-elastic FWI



The derived I_P , I_S and Poisson's ratio models using velocity-density parameterization.

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VTI-elastic FWI

Ignoring anisotropy effects may produce inaccurate velocity estimations in elastic FWI.

The vertical transverse isotropic and elastic (VTI-elastic) media can be described using velocity and Thomsen's parameters:

$$\alpha_v = \sqrt{\frac{c_{33}}{\rho}}, \beta_v = \sqrt{\frac{c_{44}}{\rho}}, \varepsilon = \frac{c_{11} - c_{33}}{2c_{33}}, \delta = \frac{(c_{13} + c_{44})^2 - (c_{33} - c_{44})^2}{2c_{33}(c_{33} - c_{44})},$$

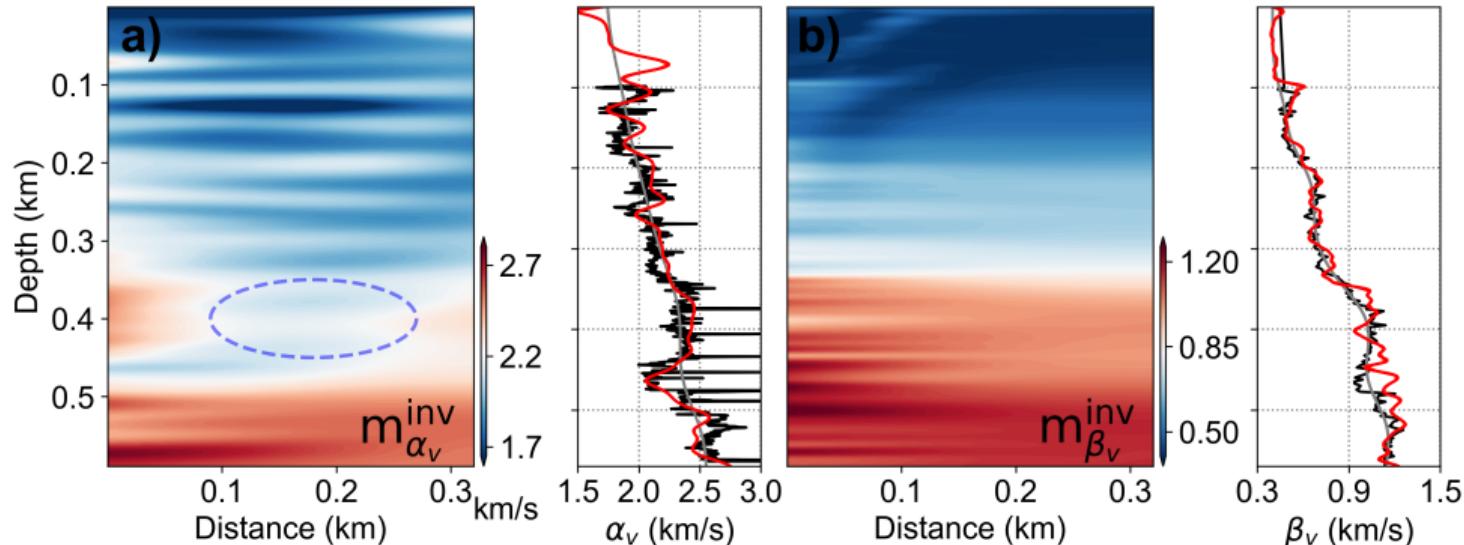
where α_v and β_v are vertical P- and S-wave velocities. ε and δ are the Thomsen's parameters.

To reduce the influences of interparameter tradeoffs, we use a new model parameterization:

$$\alpha_v, \beta_v, \alpha_h = \alpha_v \sqrt{1 + 2\varepsilon}, \alpha_n = \alpha_v \sqrt{1 + 2\delta},$$

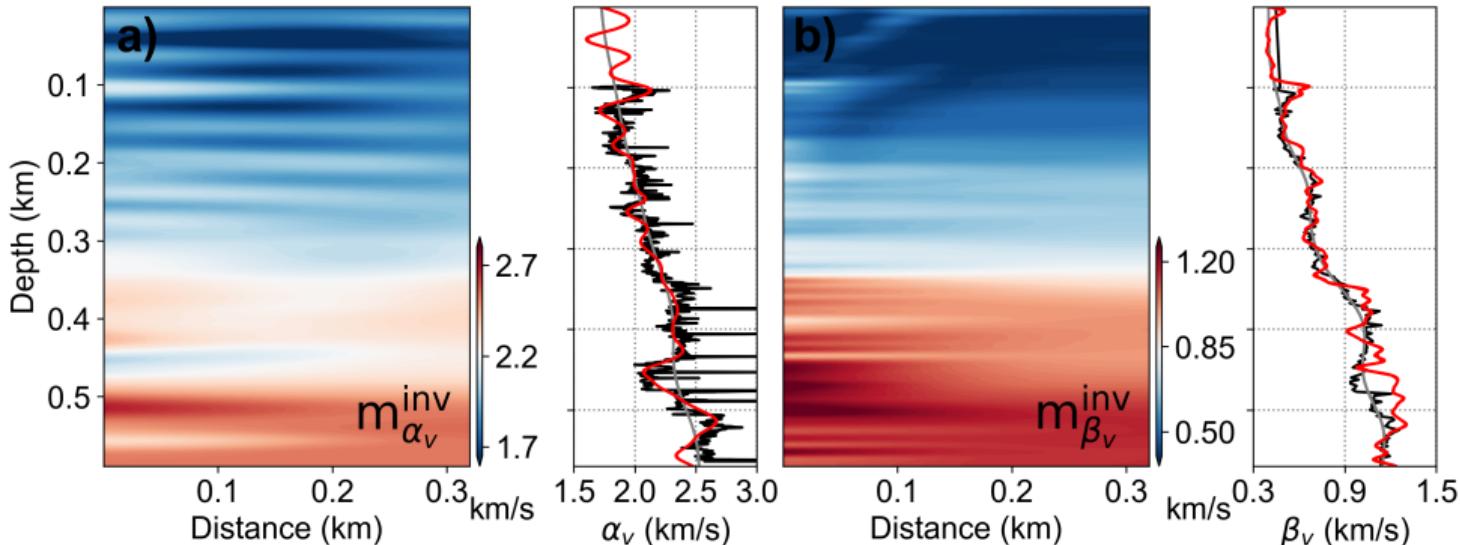
where α_h and α_n are horizontal and NMO P-wave velocities.

Isotropic-elastic FWI using EnviroVibe Source W-VSP data



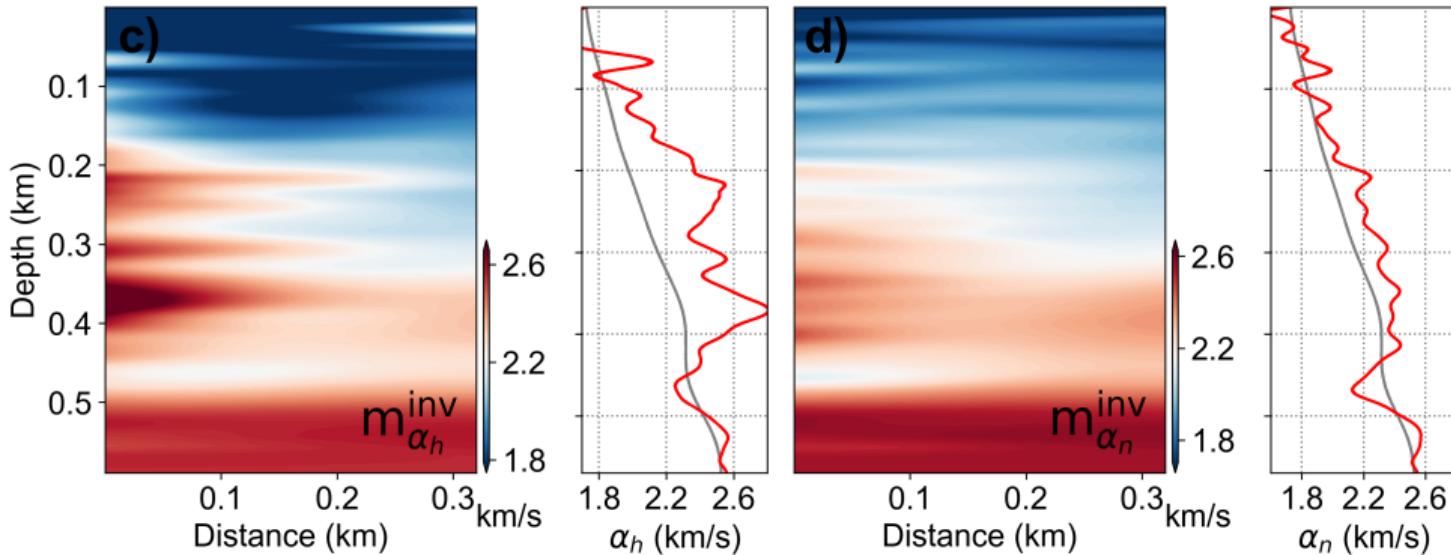
Inverted α_v and β_v models without considering anisotropy.

VTI-elastic FWI using EnviroVibe Source W-VSP data



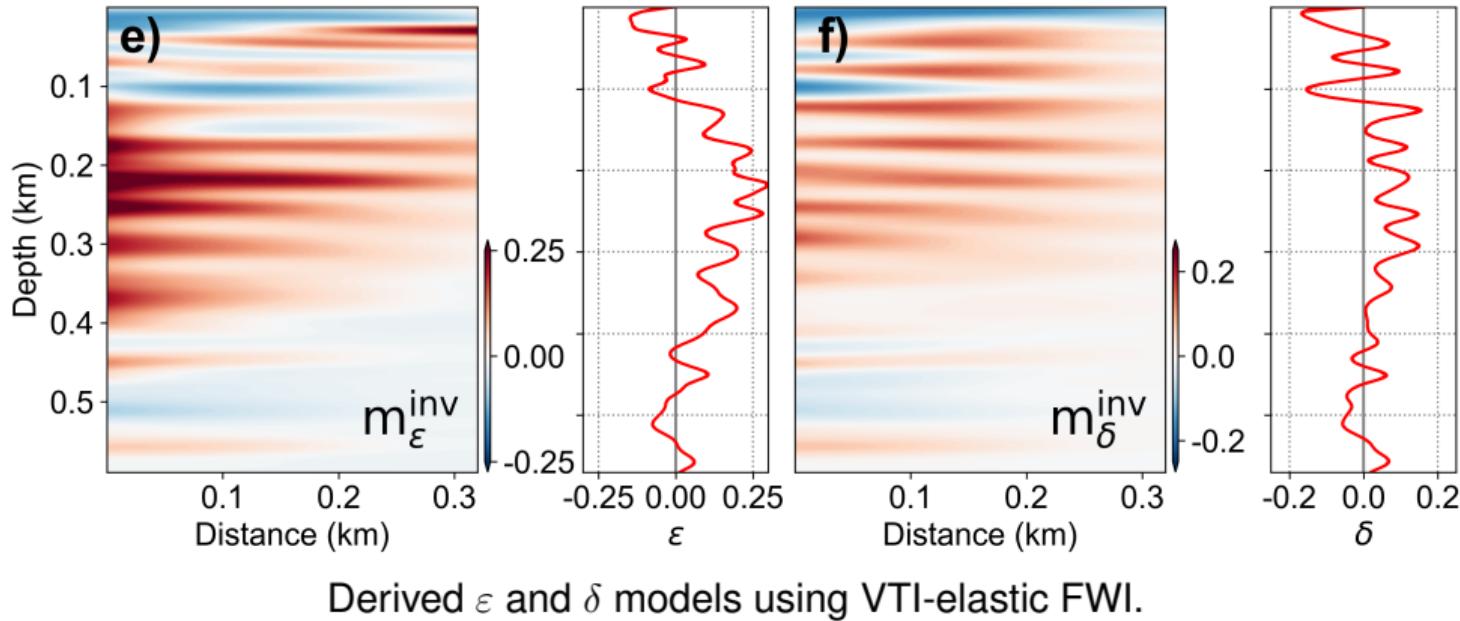
Inverted α_v and β_v models using VTI-elastic FWI.

VTI-elastic FWI using EnviroVibe Source W-VSP data

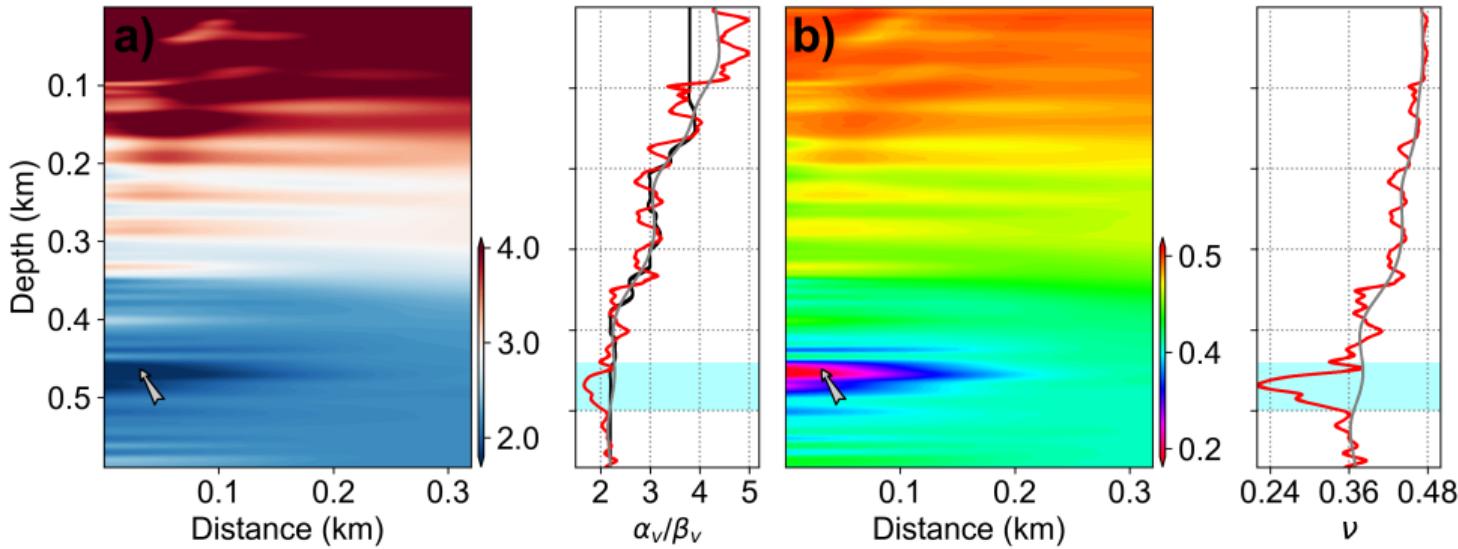


Inverted α_h and α_n models using VTI-elastic FWI.

VTI-elastic FWI using EnviroVibe Source W-VSP data



VTI-elastic FWI using EnviroVibe Source W-VSP data



Derived α_v/β_v and Poisson's ratio models using VTI-elastic FWI.

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Conclusions

- Isotropic and VTI-elastic FWI are applied to practical W-VSP data for hydrocarbon reservoir characterization.
- In isotropic-elastic FWI, the velocity-density parameterization performs best and provides more reasonable density estimations. The inverted α/β ratio and Poisson's ratio models give informative references to identify the target reservoir.
- With VTI-elastic FWI, improved velocity models are obtained. The inverted anisotropy models also provide inferences for lithology discrimination and reservoir characterization.

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Thank You!